CHANGING WHAT'S POSSIBLE

ARPA-E MOVE Annual Meeting
Home & Vehicle Refueling Projects

Performer Presentations

5-Minute Overviews

October16, 2014

Awardee Presentation Schedule

1. **Onboard Dynamics – Jeff Witwer**
   Vehicle Integrated Natural Gas Compressor

2. **Eaton Corporation – Clark Fortune**
   Near Isothermal CNG Liquid Piston Compressor

3. **University of Texas at Austin – Michael Lewis**
   Free Piston Linear Motor Compressor for Natural Gas Home Refueling

Vehicle Integrated Natural Gas Compressor

Jeff Witwer, PhD, PE
VP of Engineering
Jeff.Witwer@onboarddynamics.com

ONBOARD DYNAMICS, INC.

Combine existing resources in a novel way

- $1GGE fuel for vehicle operators (>50% reduction)
- Elimination of infrastructure problem
- Dramatic cost savings vs. building a CNG station ($500-2000 per vehicle vs. >$100K per station)

Accomplishments and Lessons

Lessons learned from Phase 1

- ✓ Bi-modal engine concept is feasible and proven
- ✓ Increasing load on engine (faster fill rate) is essential to reduce parasitic losses
- ✓ Careful head design is critical (e.g., minimize clearance volume) for maximum performance

Vehicle Integrated Natural Gas Compressor

- Experienced founding team
- Preliminary business plan
- MOVE Award received Sept 9, 2014
- Matching funds from private investors and Oregon State agencies

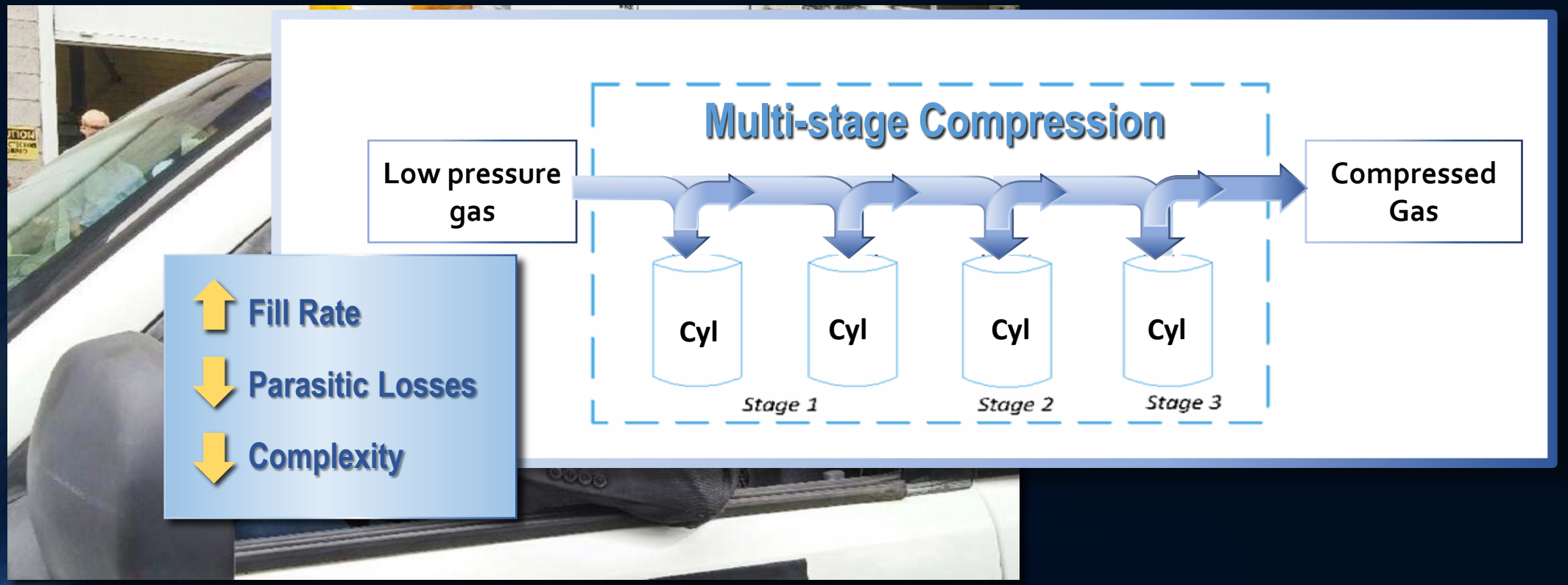
Phase 2 Key Objectives 2014-2016

- Use multiple cylinders = reduce fill time and losses
- Base on available CNG-prep V8 engine
- Fabricated and on test stand in 12 months
- Target standard production heavy duty, bi-fuel pickups in fleets too small for standard compressors
- Validate target market for early commercialization
- Refine market size and entry strategy

Completed Project and Next Phase

Phase 1: 2012-2014 Phase 2: 2014-2016

OSU/ Natural Gas Vehicle Dynamometer Onboard Dynamics Vehicle Integration Natural Gas Compressor



Execution and Transition Strategies

Commercial Production

Introduce In-Cylinder Product
- Ready for demonstration in 18 months
- To be licensed to vehicle OEMs

Introduce Aftermarket Product(s):
- Gain user experience and metrics with fleets
- Validate market interest and adoption

Product Roadmap
Initial product suitable for aftermarket installation

ARPA-E Award
Engineering and commercialization of in-cylinder technology

2014 → 2015 → 2016 → 2017

Onboard Dynamics is Hiring

Lead Project Engineer

Live and work in beautiful Bend, Oregon

For more information, visit
http://www.onboarddynamics.com/careers

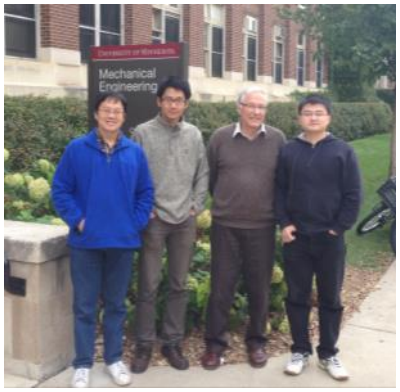
Near Isothermal CNG Liquid Piston Compressor

Eaton / University of Minnesota
Clark Fortune, Principal Engineer
248-226-6839 gclarkfortune@eaton.com

Team Members & Organizations

System and Manufacturing

EATON
Powering Business Worldwide



Modeling and Simulation

UNIVERSITY OF MINNESOTA
Driven to Discover℠

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Near Isothermal CNG Liquid Piston Compressor

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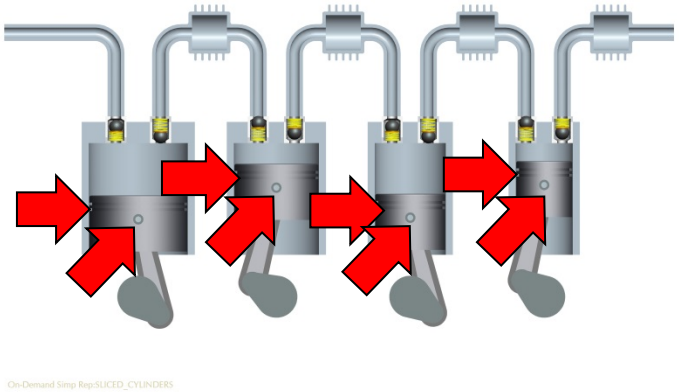
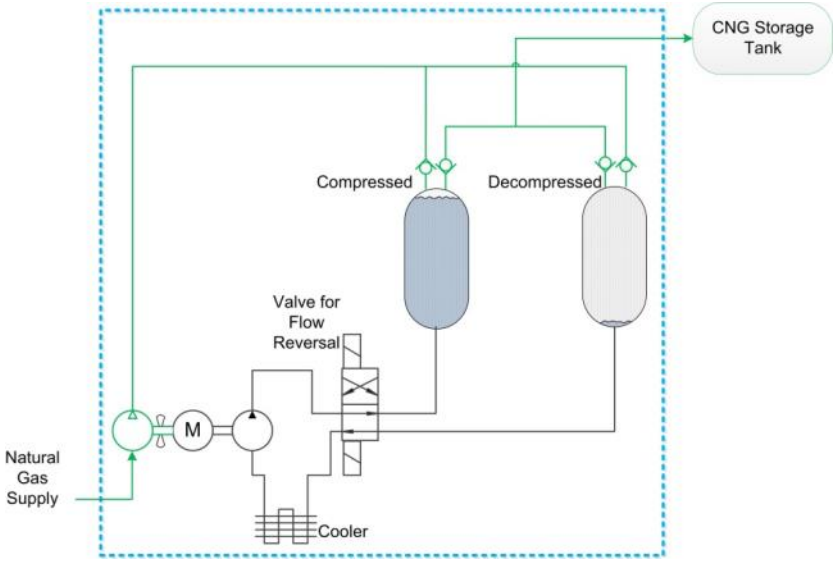
Innovation

Problem to Solve – Minimize CNG Compressor Total Owning and Operating Costs



Value Hypothesis – Eaton's Liquid Piston Compressor has higher reliability and lower maintenance requirements than today's reciprocating piston compressors.

Failure Mode	Reciprocating Piston Compressor	Eaton Liquid Piston Compressor
Piston rings, packing, bushings, crank bearings	Maintenance required	Maintenance eliminated
Life – impact by load cycling	900 cycles/minute	4 cycles/minute (longer life)
Life – impact by temperature	Internal temps 180C+	Internal temps < 60C (longer life)



Near Isothermal CNG Liquid Piston Compressor

Eaton / University of Minnesota
Clark Fortune, Principal Engineer
248-226-6839 gclarkfortune@eaton.com

Objectives

- Key Technical Targets for ARPA-E funded Prototype:
    - Peak Gas Temperature < 120 C at 10 gge/h flow and 4500 psi pressure
        - Near-Isothermal Liquid Piston Compression
    - Oil Carryover < 100 ppm
        - Industry Standard Coalescing Filter technology
- Key Challenges
    - Thermodynamic process/modeling
    - Market and Business Opportunity Quantification

Target Requirements	MOVE Targets for Home Refueler	Reciprocating Piston Compressors	Eaton Prototype Compressor	Eaton Liquid Piston Compressor
Flow Rate	1 gge/h	10 to 200 gge/h	10 gge/h	10 to 200 gge/h
Max. Pressure	3600 psi	4500 psi	4500 psi	4500 psi
Target Cost	$500 ($/gge/h)	1600 to 5000 ($/gge/h) *		1600 to 5000 ($/gge/h)*
Operating Life	10 y	10-20 y	1000 h	> 20 y

* Source: Margaret Smith, John Gonzales. "Costs Associated with Compressed Natural Gas Vehicle Fueling Infrastructure-Factors to consider in the implementation of fueling stations and equipment." Clean Cities, Office of Energy Efficiency and Renewable Energy, US Department of Energy. Report Sept 2014. Print.

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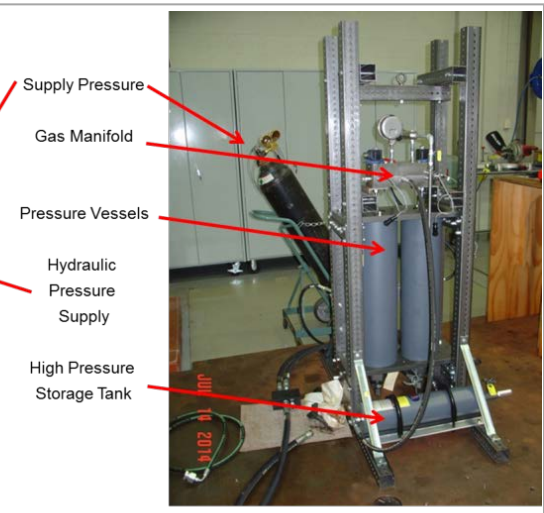
Accomplishments Phase 2 (4Q13 – 3Q14)

- ✓ **Selection of working fluid**
- ✓ **Lab experimentation →**
  - ✓ Liquid Piston Compression of Nitrogen
  - ✓ Thermodynamic Model Validation
  - ✓ Identification of new issues – CR control
- ✓ **Methane solubility** – novel engineering solution conceived.

- ✓ **Learnings and how we changed our approach**
  - ✓ Light-duty CNGV payback time
    - ✓ Niche unless payback < 2 y
    - ✓ Home Refueling Market = f(LD CNGV mkt)
  - ✓ Commercial Vehicle CNGV growth here now
  - ✓ Pivot to Commercial Vehicle CNG Compressors



- **Key technical challenges left to mitigate**
  - Oil carryover, methane solubility, controlling compression ratio

Planned Activities – Phase 3 (4Q14 – 4Q15)

- **Develop Compressor System Prototype**
  - Revise design
  - Procure and build
  - Commission/characterize
  - Test
- **Technology to market – Business Case Development**

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Transition

Assuming technical success:

Eaton will continually assess commercial viability and opportunity.

- Eaton will accelerate or decelerate development efforts accordingly.

Eaton would like to discuss possible next steps with potential customers/partners.

- What channel partners would be interested in working with us to evaluate/demonstrate/develop the offering?
  - Compressor packagers
  - Station integrators/developers
  - End users
- What might a demonstration project look like?
- What external funding might be available for joint efforts?

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Free Piston Linear Motor Compressor for Natural Gas Home Refueling

University of Texas - Center for Electromechanics
Michael Lewis, Sr. Engineer Scientist (PI)
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Project Team

University, Non-profit R&D organization, and National Lab with strong ties to private industry and successful track record of bringing new technologies to market.

The University of Texas at Austin
Center for Electromechanics

Gas Technology Institute

Argonne NATIONAL LABORATORY

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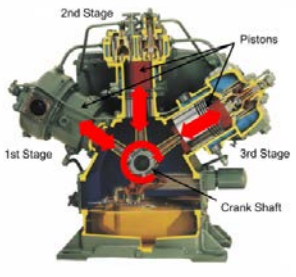
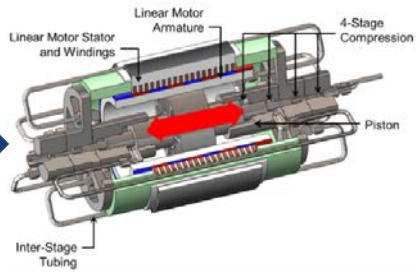
Innovation

REDUCED COMPLEXITY AND COST



Reciprocating Compressor



Free Piston Linear Motor Compressor

Metric	Current	MOVE	UT-CEM
Cost	$4,000	$500	*$2,000 **
Parasitic Load (kWh/GGE)	1.7	<1.7	*<1.7*
Flow Rate (GGE/hr)	0.5 - 1	1	*1*
Fill Pressure (bar)	250	250	**250**
Life (hrs)	<5,000	15,000	**>>5,000**
Weight (lbs)	150	50	**100**

Increased Efficiency
- Single moving part with no motion conversion
- Resonant frequency operation
- Dry, low friction seals with no oil carryover

Increased Life
- Reduced part count and serviceable design
- Near frictionless carbon seals with low wear

*** Free Piston Linear Motor Compressor HRA Cost**

Compressor –	**$500 - 750**
HRA accessories –	**$500 - 800**
HRA Installation –	**$500**
Total Installed Cost –	**$2000**

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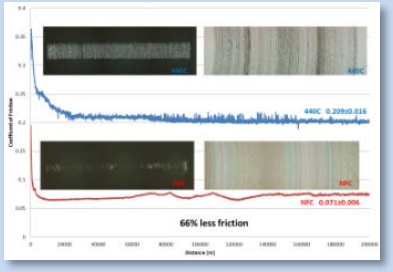
Accomplishments

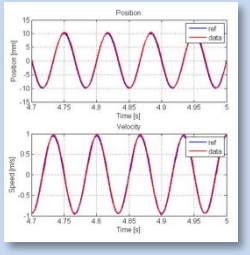
Seal and Coating Development
- Tested two dozen NFC seal and coating systems
- Achieved friction coefficient of 0.05
- Demonstrated >3,000 hr seal life and still counting!
- Passed seal life Go/No-Go decision point

Linear Motor Design and Testing
- Studied 6 linear motor variants, balancing performance and cost
- Demonstrated resonant frequency operation and tight position control surpasses MOVE efficiency targets

Compressor Design and Testing
- Engineered and tested custom valves
- Optimized intercooler design for cost
- Designed compressor for serviceability

Patent Application Filed
- Covers free piston linear motor compressor system
- Separate filings being considered for subsystems





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Next Activities – Demonstration testing!

Completed 38 of 48 project milestones

Laboratory Demo Unit
- Testing to begin end-2014
- Undergo 1,000 hour demonstration by mid-2015

Second Demo Unit fabrication nearly complete
- Testing to begin early-2014
- Thermal testing at high/low ambient temps
- Recommendation of team advisory panel

Demonstrate reliable and continuous operation under varying ambient thermal conditions

Transition

Team composed of three non-profit entities with no Industrial Partner on team lined up to make transition to commercialization easily

The University of Texas at Austin Center for Electromechanics

Gas Technology Institute

Argonne NATIONAL LABORATORY

Commercialization pathway has not been established
- **Start-up business, licensee deal, or joint development partnership**

Next Stage Tasks:
- **Refine Prototype**
- **Engineer Pre-production Compressor**
- **Develop and Package as HRA**
- **Carry-out Field Demos**
- **Obtain Regulatory Certification**

Seeking funding and partners for next stage prototype development prior to field demos

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